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Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

A new ecohydrological model based on Richard equation.

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Abstract

The evapotranspiration is a key term in the hydrological water balance of the Mediterranean ecosystems because can reach the same values of the annual precipitation [2], [36]. In this work a typical heterogeneous ecosystem is considered, it includes 3 cover types: the bare soil and two different Plant Functional Types (PFTs, e.g., grass and woody vegetation) because the presence of the two PFTs in the same system plays a crucial role in the development of water use strategies. In Mediterranean ecosystems the competition of the different vegetation types for the water use is very important, especially during the water stress periods (spring and summer) that are crucial for the management and the planning of the water resources.

In the present work a new ecohydrological model based on Richard equation has been developed to simulate numerically the vertical soil moisture variability and the vertical distribution of plant roots. The root distribution of the two PFTs considered, is an important term to quantify the root water uptake and the different strategies developed by the species in drought conditions. Two vegetation dynamic models (VDMs) coupled with the Richard model simulate the physiological trials of the plants in terms of distribution and evolution of the radical systems in the soil of the two PFTs, using a macroscopic approach.

The model has been applied to the experimental site of Orroli in the Mid-West of Sardinia (Italy).

Results show a good performance of the model in terms of soil moisture and evapotranspiration. The two species show a different behavior in terms of root distribution during the drought periods (summer).

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1. Introduction

In the hydrological water balance of the Mediterranean water – limited ecosystems the evapotranspiration (ET) is the leading loss term of the root-zone water budget with a yearly magnitude that may be roughly equal to the precipitation [2], [35]. These Mediterranean ecosystems are commonly heterogeneous savanna-like ecosystems, with contrasting plant functional types (PFTs, e.g., grass, shrubs and trees) competing for the water use [2],[35]. Despite the attention these ecosystems are receiving, a general lack of knowledge persists about the relationship between ET and the plant survival strategies for the different PFTs under water stress. Indeed, for surviving the different PFTs adapt their radical systems (in terms of depth and vertical distribution) to the soil moisture content profile, but at the same time the species compete between them for the water use.

The development of complex and detailed physical based ecohydrological models help investigating these complex processes. Only the use of Richard's equation based model allows modeling the dynamics of soil moisture profile and its interactions with the competitive PFT root systems.

Indeed, Montaldo et al. (2008) [24] developed a coupled land surface model (LSM) and a vegetation dynamic model (VDM) that consider the interaction between the different PFTs, but simplify the dynamics between soil moisture profile and plant root distributions using a simple two-layer soil model. On the other hand different models based on the Richard equations that consider the root uptake have been developed [8], [10], [21], [29], but they consider only one PFT and neglect the competition between the antagonist vegetation species.

A key term of the competition modeling between PFTs is the plant root water uptake. There are two main approaches for modeling the plant root uptake, the microscopic and the macroscopic approaches [5], [12], [13], [22]. The microscopic approach is more physically based and simulates the water dynamics of each single root [8], [12], [25], [28], [31]. Therefore, it needs the detailed plant root geometry and root information and properties, which are difficult to know usually [34]. Instead in the macroscopic approach the whole root system is modeled and the vertical distribution is function of the soil moisture vertical profile. This approach needs less parameters, which are also usually available, so that the use of macroscopic approach is generally favored in many hydrological applications [5], [13], [21], [33].

Feddes et al. (1978) [11] proposed a macroscopic root uptake approach where the potential transpiration is first distributed vertically in the root zone and then correct with a reduction function (of the actual evapotranspiration). From this model different vertical distribution functions are developed both linear [5], [13], [29] and nonlinear [16], [21], [22], [30], [32], [33], [34] with soil moisture profile. The linear functions need less information but are less accurate than the nonlinear functions.

Hence, we propose a new LSM-VDM coupled model, which simulate soil moisture dynamics through a Richards equation based model distinguishing two main PFTs (grass and woody vegetation), which compete for the water use along the soil vertical profile, and simulate the plant root system using a macroscopic approach and the plant root distribution with a nonlinear function of the soil moisture.

2. Model description

The proposed model couples a LSM and the VDM of Montaldo et al. [23]. The LSM scheme is in Figure 1. It is based on an adapted version of the Richard's equation, which includes the root water uptake [17], for the θ soil moisture modeling along the z vertical axis expressed in discrete form as:

$$\frac{\Delta \theta}{\Delta t} = \frac{\Delta}{\Delta z} \left[K \frac{\Delta \psi}{\Delta z} \right] - \frac{\Delta K}{\Delta z} - S_{ET,i} \quad (1)$$

where Δt is the time step, K is the soil hydraulic conductivity [4], ψ is the soil water potential and $S_{ET,i}$ is the sink term of the i^{th} soil layer at depth z_i , estimated by:

$$S_{ET,i} = f_{v,g} S_{g,i} + f_{v,wv} S_{wv,i} + f_{bs} S_{bs,i} \quad (2)$$

where $S_{g,i}$, $S_{wv,i}$ are the sink terms of grass and woody vegetation of the i^{th} soil layer respectively, $S_{bs,i}$ is the soil evaporation of the i^{th} soil layer, $f_{v,g}$ and $f_{v,wv}$ and $f_{v,bs}$ are the fractions of grass, woody vegetation and bare soil respectively. The VDM estimates biomass, the $f_{v,g}$, $f_{v,wv}$ and $f_{v,bs}$ and the Leaf Area Index (LAI) of the two PFTs [23], [24]. Soil parameters are in Table 1.

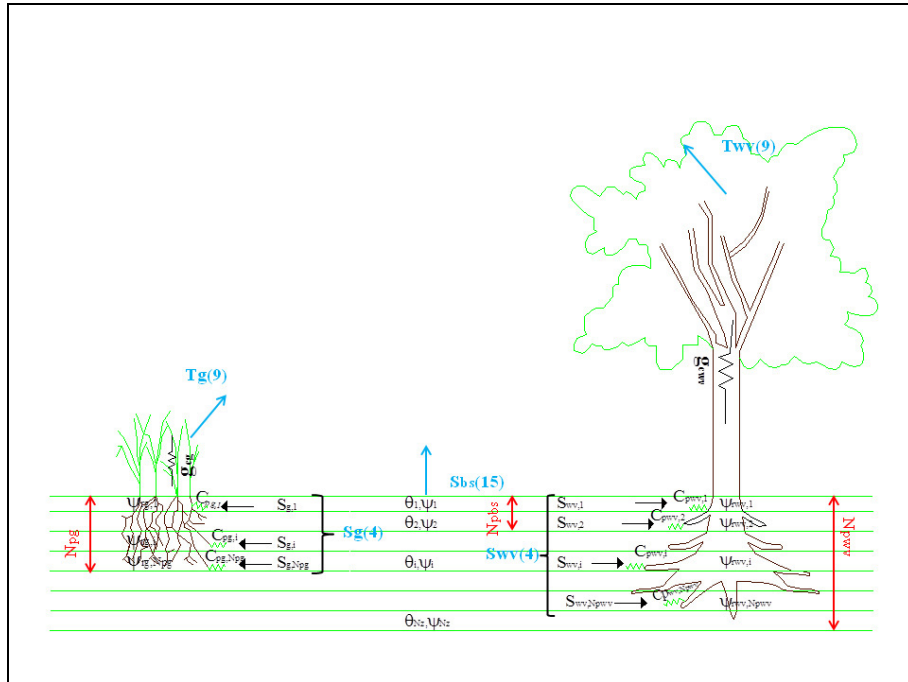


Fig. 1. Schematic representation of the soil water balance model. In brackets the equations for each process.

The total evapotranspiration is estimated by

$$ET = f_{v,g} \sum_{i=1}^{N_{pg}} S_{g,i} + f_{v,wv} \sum_{i=1}^{N_{pwv}} S_{wv,i} + f_{bs} \sum_{i=1}^{N_{pbs}} S_{bs,i} \quad (3)$$

where N_{pg} and N_{pwv} are the numbers of Δz soil layers within the root zone of grass and of woody vegetation and N_{bs} is the number of Δz soil layers from surface for the soil evaporation.

Sink terms of grass and woody vegetation are estimated from the Gardner model (1960) [9]. In the following we describe the equations of the transpiration and root water uptake of the two PFTs. For avoiding redundancies hereafter we use the symbol x for indicating the generic plant species (i.e. $x = g$,

wv), because the equations are the same for both the PFTs. The rate of the root water uptake is proportional to the gradient between the soil water potential and the root water potential through [10], [12]:

$$S_{x,i} = C_{px,i}(\psi_{s,i} - \psi_{rx,i})\xi_{x,i}RLD_x \quad (4)$$

where $\psi_{s,i}$ is the soil water potential at the i^{th} soil layer, $\psi_{rx,i}$ is the root potentials of the x^{th} plant species at the i^{th} soil layer, VPD is the vapor pressure deficit, $\xi_{x,i}$ is the root distribution within the root zone of the x^{th} plant species [4] at the i^{th} soil layer, RLD_x is the root length density of the x^{th} plant species, $C_{px,i}$ is the root conductivity of the x^{th} plant species at the i^{th} soil layer and is estimated by [4]:

$$C_{px,i} = K_{so,x} \left(\frac{\theta_i}{\theta_s} \right)^{2b_x+3} \quad (5)$$

where $K_{so,x}$, and b_x are vegetation parameters (Table 2). $\xi_{x,i}$ is estimated from the soil shear strength $ss_{x,i}$ of the x^{th} plant species at the i^{th} soil layer [4] defined as [5]:

$$ss_{x,i} = ss_{max,x} [1 - \theta_i]^3 \quad (6)$$

where $ss_{max,x}$ is the maximum soil share strength (i.e., dry soil). Hence, the root distribution is given by [5]:

$$\xi_{x,i} = \frac{1 - \frac{ss_{x,i} - ss_{min,x}}{ss_{max,x} - ss_{min,x}}}{\sum_{i=1}^{Np,x} \frac{ss_{x,i} - ss_{min,x}}{ss_{max,x} - ss_{min,x}}} \quad (7)$$

where $ss_{min,x}$ is the minimum soil share strength (i.e., saturated soil). RLD_x per unit soil volume is estimated by [6], is

$$RLD_x = \frac{B_{r,x}c_{r,x}}{UnitVolume} \quad (8)$$

where $B_{r,x}$ is the root biomass of the x^{th} plant species and is estimated by the VDM [23] and $c_{r,x}$ is the specific root length of the x^{th} plant species (Table 2).

For estimating $S_{ET,i}$ from (4), the root water potentials still need to be estimated. In this sense, we propose a new approach. Indeed we estimate the transpiration of each plant species at each soil layer both using (4), that is from the gradient of water potential between the soil and the plant roots, and using the widely used Jarvis approach [15], that is from the atmospheric and environmental conditions through the plant conductivity. Plant root water potentials are the unknown terms of both the equations, so that we close the model matching the two expressions of the transpirations.

Indeed, the transpiration of the x^{th} plant species at the i^{th} soil layer is also estimated using the Jarvis

(1976) approach [15]:

$$T_{x,i} = g_{cx,i} VPD = f_{1,x}(\psi_{rx,i}) f_{2,x}(T_a) g_{smax,x} LAI_x VPD \quad (9)$$

where $g_{cx,i}$ is the canopy conductivity of the x^{th} plant species at the i^{th} soil layer, $g_{smax,x}$ is the maximum stomatal conductivity of the x^{th} plant species (Table 2), LAI_x is the leaf area index of the x^{th} plant species [19], and $f_{1,x}$ and $f_{2,x}$ relate canopy conductivity to soil moisture and air temperature (T_a) stresses, respectively. The effect of the soil moisture content is estimated by [10], [17, eq. 6.153b, 6.153c, 6.153d]

$$f_{1,x}(\psi_{rx,i}) = \begin{cases} 0, & \text{if } \psi_{rx,i} \leq \psi_{wp,x} \\ \frac{\psi_{rx,i} - \psi_{wp,x}}{\psi_{lim,x} - \psi_{wp,x}}, & \text{if } \psi_{wp,x} < \psi_{rx,i} < \psi_{lim,x} \\ 1, & \text{if } \psi_{rx,i} \geq \psi_{lim,x} \end{cases} \quad (10)$$

where $\psi_{lim,x}$ and $\psi_{wp,x}$ are the critical water potential and the wilting point of the x^{th} plant species respectively [16] (Table 2).

The effect of air temperature on the stomata opening is estimated by [20], [24]:

$$f_{2,x}(T_a) = \begin{cases} 0 & \text{if } T_a \leq T_{a,min,x} \text{ and } T_a > T_{a,max,x} \\ 1 - \frac{T_{a,opt,x} - T_a}{T_{a,opt,x} - T_{a,min,x}} & \text{if } T_{a,min,x} < T_a < T_{a,opt,x} \\ 1 & \text{if } T_{a,opt,x} \leq T_a \leq T_{a,max,x} \end{cases} \quad (11)$$

where $T_{a,min,x}$, $T_{a,opt,x}$ and $T_{a,max,x}$ are the minimum, optimum and maximum temperature of the x^{th} plant species respectively [20], [24] (Table 2).

Then, since $S_{x,i}$ estimated from (4) and $T_{x,i}$ estimated from (9) are same quantities because are both the transpiration of the x^{th} plant species at the i^{th} soil layer, we match the two equations, close the system of equations (1), (2), (4) and (9) and obtain $\psi_{rx,i}$:

$$\psi_{ri,x} = \begin{cases} \frac{\psi_{s,i} A_{x,i} (\psi_{lim,x} - \psi_{wp,x}) + T_x^* \psi_{wp,x}}{A_{x,i} (\psi_{lim,x} - \psi_{wp,x}) + T_x^*} & \text{if } \psi_{rx,i} \leq \psi_{wp,x} \\ \psi_{s,i} - \frac{T_x^*}{A_{x,i}} & \text{if } \psi_{wp,x} < \psi_{rx,i} < \psi_{lim,x} \\ \psi_{s,i} - \frac{T_x^*}{A_{x,i}} & \text{if } \psi_{rx,i} \geq \psi_{lim,x} \end{cases} \quad (12)$$

where

$$A_{x,i} = C_{px,i} \xi_{x,i} RLD_x \quad (13)$$

$$T_x^* = g_{s\max,x} LAI_x f_{2,x}(T_a) VPD \quad (14)$$

The estimated root potential allows to close the system of equations (1), (2), (4) and (9), and estimate the soil moisture dynamics. Equation (1) is integrated using the widely used predictor-corrector method [14]. Finally soil evaporation at the i^{th} soil layer is given by

$$S_{bs,i} = \frac{\alpha(\theta_g) E_{bs}}{N_{pbs}} \quad (15)$$

where θ_g is the surface soil moisture and is the mean soil moisture values of the N_{pbs} shallow soil layers, $\alpha(\theta_g)$ is a polynomial function [28], E_{bs} is the potential evaporation estimated by the Penman equation [3, eq. 10.15, 10.16, 10.19]

Table 1. Soil parameters.

Parameter	Description	Value
θ_s [-]	Saturated soil moisture	0.55
$ \psi_s $ [m]	Soil potential at saturation	0.40
k_s [m/s]	Conductivity at saturation	$2 \cdot 10^{-7}$
b_s [-]	Slope of the retention curve	3.5

3. Case study

The case study is situated in Orroli, Italy, on the island of Sardinia (39° 41' 12. 57" N, 9° 16' 30. 34" E, 500 m a. s. l.). This area is a typical Mediterranean landscape with a patchy mixture of trees, mainly wild olive (*Olea sylvestris*) of height approximately 3.5-4.5 m, and a few cork oaks (*Quercus suber*) of height approximately 6-7 m, shrubs (*Asparagus acutifolius* and *Rubus ulmifolius*), creepers of the wild olive trees (*Crataegus azarolus* and *Smilax aspera*), and C3 herbaceous (grass) species (*Asphodelus microcarpus*, *Ferula comunis*) that are present in live form only during wet seasons and reach heights of approximately 0.5 m. The soil is thin, the thickness varies from 10-30 cm. It is a mainly silt loam soil (19 % of sand, 76% of silt, 5% of clay) with a bulk density of 1.38 g/cm³ and a porosity of 53%.

Table 2. Vegetation parameters.

Parameter	Description	Grass	Woody Vegetation
$r_{s,min}$ [s m ⁻¹]	Minimum stomatal resistance	180	250
T_{min} [°K]	Minimum temperature	272.15	272.15
T_{opt} [°K]	Optimum temperature	295.15	293.15
T_{max} [°K]	Maximum temperature	313.15	316.15
$ \psi_{wpl} $ [m]	Wilting point	30	210
$ \psi_{lim} $ [m]	Limiting water potential for vegetation	130	600
K_{so} [m/s]	Specific conductivity	10 ⁻¹	3
B [-]		3.4	3.8
ss_{min} [MPa]	Minimum resistance	2	5
ss_{max} [MPa]	Maximum resistance	7	12.8
c_r [m gDM ⁻¹]	Specific root length	[18]	[1]

4. Results

Comparison between modeled and observed values of the two key model outputs, soil moisture and evapotranspiration, are reported in Figures 2 and 3.

Three periods are distinguished for evaluating the model performance: 2003-2005 is the calibration period, 2006-2007 is the first validation period (hereafter 1Val), and 2008-2009 is the second validation period (hereafter 2Val). The statistic parameters (mean error (hereafter ME) and Root Mean Square Error (hereafter RMSE) of the tree periods are in Table 3. Errors of the model are low for both the calibration period and the two validation periods. Note from Figure 3 that the modeled cumulative evapotranspiration is close to the observed evapotranspiration, with a difference of 6% of the total evapotranspiration.

Table 3. Statistical parameters of the performance model.

	Humidity		Evapotranspiration	
	ME	RMSE	ME	RMSE
Calibration (2003-2005)	0.0476	0.0658	0.6867	0.9905
I° Validation (2006-2007)	0.0629	0.0571	0.7813	1.0278
II° Validation (2008-2009)	0.0786	0.0981	1.0832	1.2582

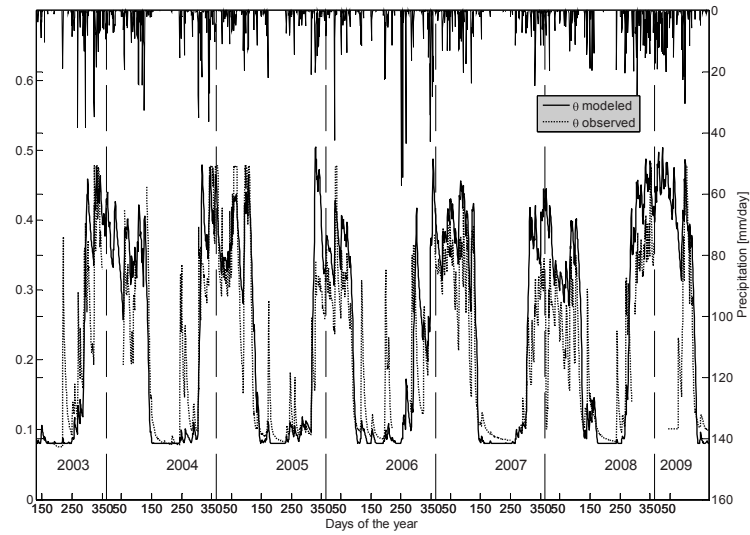


Fig. 2. Mean daily soil moisture content in the root zone.

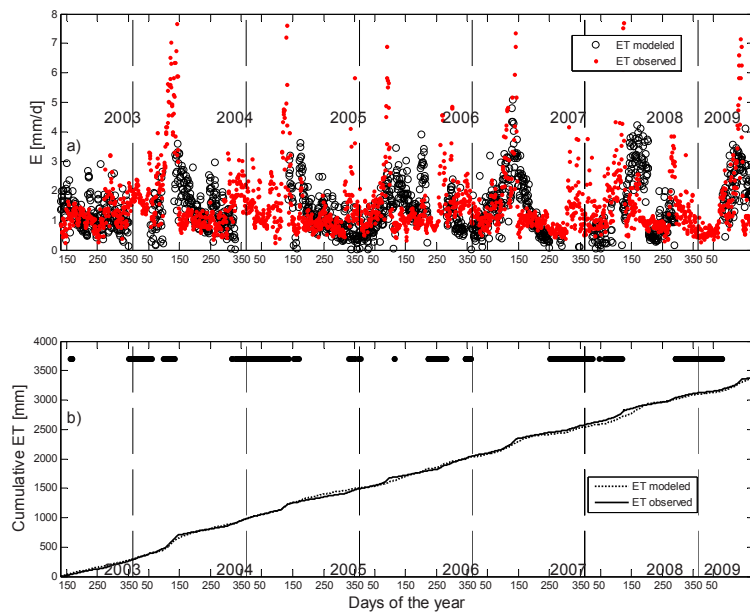


Fig. 3. (a) daily evapotranspiration; (b) cumulative evapotranspiration

5. Conclusions

An innovative model, which is based on the Richards equation for soil moisture dynamics modeling and includes two competitive plant species (grass and woody vegetation) for the water use is proposed. The competition between plant species is detailed represented and the root potentials of the two plant species and their interactions with soil moisture vertical profile are also modeled through the closure of a system of equations for the transpiration estimate, which allows to account for both moisture gradient between plant root and soil and atmospheric and environmental conditions. The proposed model simulates correctly soil moisture and plant dynamics in the water-limited case study of Orroli (Sardinia). The model allows simulating behavior strategies of the different plant species for optimizing root water uptake against antagonistic plants, which is the key element for the plant survival in water limiting conditions. Hence, the model can be employed for investigating plant strategies under desertification and climate change scenarios.

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